Effects of Eocene Global Events on Marine Bivalves from Kutch and Cambay Basins of Gujarat, India

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Synopsis of Thesis

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A) Introduction

The Eocene epoch had experienced a wide spectrum of geological events ranging from tectonic rearrangements to climatic changes. Journey of the Indian and African plate towards Eurasian plate, shallowing of the Tethyan gateway (Heydt and Dijkstra, 2006), and opening of the Drake passage (DP) (Scher and Martin, 2006) and Tasmanian gateway (TG) (Huber and Nof, 2006) are the determining factors behind the major changes in Oceanic circulation pattern and shifting of faunal diversity hotspots (Renema et al., 2008) during this period.

The early Eocene (Ypresian) is marked by several large to small scale hyperthermal events. A large amount of isotopically light carbon (^{12}C) was released in the ocean-atmosphere system, which is indicated by negative carbon isotope excursions (CIE) in the $\delta^{13}C$ curve of various proxies. The Paleocene-Eocene Thermal Maximum (PETM) is the most well-known of these hyperthermals and most widely reported from all over the world by a prominent excursion of the $\delta^{13}C$ curve of marine sedimentary and carbonate records at the Paleocene-Eocene (P-E) epoch boundary (~56Ma) (Giusberti et al., 2007; Sluijs et al., 2008, 2011; Westerhold et al., 2018). The PETM was followed by several relatively smaller hyperthermal events during the early Eocene, which are ETM2 or H1 (~54.09 Ma), H2 (~54 Ma), I1 (~53.65 Ma), I2 (~53.55 Ma), J (~53.15 Ma) and ETM3 (~52.8 Ma) (Lauretano, 2015; Westerhold et al., 2007, 2018). The greenhouse earth of the Eocene transitioned into icehouse with a cooling in the late Eocene, named the 'Terminal Eocene Event', which culminated in global cooling and formation of Antarctic cryosphere at the Eocene- Oligocene (E-O) boundary. There was a global transgression, which has been recorded from tropical and also higher latitudes, occurring more or less concomitant with PETM (Speijer and Morsi, 2002; Sluijs et al., 2008; Schulte et al., 2011; Pujalte et al., 2014).

The Indian subcontinent was in the equatorial region during early Eocene, in the course of its dramatic voyage from the southern to the northern hemisphere, after separation from the Gondwanaland in the Early Jurassic (Smith et al., 1994; Scotese, 2016). The Cenozoic sediments were deposited from the Indus Valley (Pakistan) in the west to Brahmaputra River Valley (India) in the east along the

Himalayan southern flank. Some basins in the coastal areas of western India such as Jaisalmer, Barmer and Bikaner basins of Rajasthan, and Kutch and Cambay basins of Gujarat record thick successions of the Cenozoic rocks.

Bivalves (Mollusca), one of the most common members of the Cenozoic marine benthic community, were quite diverse throughout the Eocene and occupy infaunal as well as epifaunal habitats. Their ontogeny commonly involves short or long planktotrophic larval stage, which is critical for their geographic dispersal. The shallow water current carries planktotrophic larvae (Jablonski, 1983) and oceanographic barriers influence the faunal diversity in different latitudinal ranges (Roy et al., 1994). The marginal marine settings of early Eocene Kutch and Cambay basins house a diverse assemblage of bivalve species, keeping pace with the hyperthermal and transgressive events.

1. Background Study:

a) Eocene Bivalves:

The first report of Cenozoic molluscs of Indian subcontinent was by Sowerby (1840), where only 8 Paleogene bivalves were documented from the Bartonian of Kutch. D'Archiac and Haime (1854), Cossmann and Pisscarro (1927), Vredenburg (1928a), Cox (1930, 1931a,b, 1938), Vokes (1937), Eames (1951) and Iqbal (1969a,b, 1972) documented Eocene Bivalvia from the Indus Valley basin of Pakistan, and Subathu Formation of India. Mathur (1975), and Bhatia and Khosla (1978) have documented some bivalves from the Lutetian of Subathu Formation in lesser Himalaya and Khuiala Formation of Jaisalmer basin in Rajasthan. After Sowerby (1840), post-Eocene bivalves from Kutch received some palaeontological attention (Vredenburg, 1925, 1928b) whereas Eocene bivalves were neglected. Recent investigations started to throw light on the bivalves from the Paleogene of Kutch (Tandon 1971; Kachhara et al., 2011; Halder and Bano, 2015), but still remained quite inadequate.

A recent study reveals a diverse assemblage of bivalves from the Eocene of Kutch basin encompassing 40 species among which 16 are new (Halder et al., unpublished data). Cambay basin, mainly its lignite mine sections, also unearthed a diverse well-preserved bivalve fauna in very recent times, which

remained poorly attended till date except two *Caestocorbula* species (Roy and Mukherjee, 2017) and a monogamic oyster (Halder and Mitra, 2021) from the Mangrol lignite mine section.

b) Early Eocene Hyperthermals:

Five hyperthermal events, which are PETM, ETM2/H1, H2, I1 and I2, from Vastan and Valia mines of the Cambay Basin, have been reported (Clementz et al., 2011; Samanta et al., 2013, 2016). PETM and ETM2 was reported from the Panandhro mine of Kutch basin and four other western Indian lignite mine sections (Khozyem et al., 2013, 2021; Agrawal et al., 2017).

c) Relation between Hyperthermals and Transgression:

A transgression associated with the PETM is documented globally in areas dispersed from high southern to high northern latitudes and palaeo-tropics (Sluijs et al., 2008, 2011, 2014; Pujalte et al., 2014). There are some doubts regarding the causal link between these two events (Sluijs et al., 2008). A transgression possibly coincident with ETM2 was also reported (Sluijs et al., 2008). Transgression associated with any other hyperthermal is not known.

d) Palaeobiogeographic Study:

Palaeobiogeographic study encompassing the Tethyan gateway has been carried out quite extensively by Harzhauser et al. (2002) and Bosboom et al. (2017). Das and Halder (2018), in their global palaeobiogeographic analysis on the Paleocene and Eocene gastropods, revealed high affinity of Western Indian Province (WIP) with Tethyan Europe and Gulf Coastal Plain provinces. Sinha and Halder (2018) also demonstrated high similarity in coral composition between WIP and Tethyan Europe during the Oligocene.

2. Objective of this Study:

The basic objectives of the study are as follows-

1. Documentation of the hyperthermal events in Kutch and Cambay basins through analyses of stable isotopes.
2. Identification of transgressive events from sedimentological and palaeontological criteria.

3. Documentation of the Eocene bivalve faunas from these basins.
4. Documentation of changes in the faunal composition, morphology and palaeobiological attributes of certain lineages of bivalves.
5. Search for possible link between hyperthermal and transgressive events, and in turn, their relative influences on the bivalve communities – their composition, palaeobiogeographic distribution and palaeobiological features.

3. Geological Setting:

Kutch, a pericratonic and Cambay, an intracratonic rift basin in the western boundary of the Indian subcontinent (Figure 1) host a thick pile of Paleocene-Eocene sedimentary succession along with lignite seams, deposited over the peneplained Deccan Trap (Biswas, 1992; Sahni et al., 2006; Prasad et al., 2013; Saraswati et al., 2018).

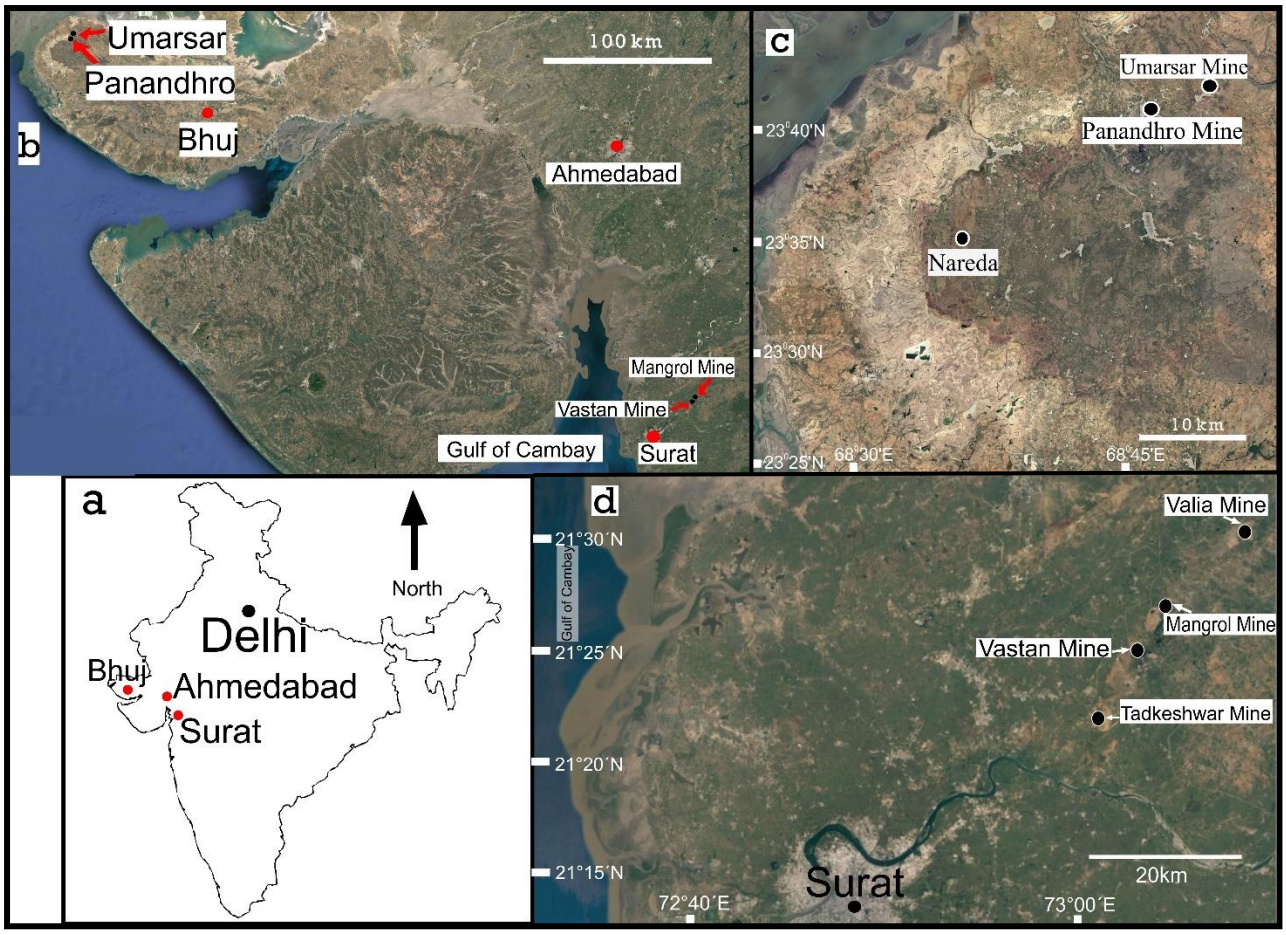

Figure 1. Map of the study area. a) Index map of India; satellite images (source: google earth) of b) the study areas; c) location of the Umarsar mine in Kutch basin; d) the four lignite mines in Cambay basin.

The presence of age-diagnostic chordate fossils, dinoflagellate cysts, index foraminifera *Nummulites burdigalensis burdigalensis*, larger benthic foraminifers, and time calibrations using strontium and argon isotope ratios indicate an age of Ypresian of the lignite bearing successions in the Panandhro and Vastan lignite mines of Kutch and Cambay basins respectively (Bajpai and Theweissen, 2002; Sahni et al., 2006; Garg et al., 2008; Punekar and Saraswati, 2010; Samanta et al., 2013; Khozyem et al., 2021 and references therein).

The lignite seams of the opencast mines of Cambay basin have been termed as Lignite seam (LS) 1 to 5 from top to bottom according to their appearance in the studied sections of the open-cast lignite mines (Figure 2). A green/grey shale unit between LS3 and 4 in Valia mine contain spheroidal concretions with molluscan internal moulds as nucleus. Thin molluscan concretionary units within shale have also been found from the other mine sections (Figure 2). The fossiliferous marine mollusc rich shell beds and concretionary units in Mangrol (within LS1 and 2), Vastan (within LS1 and 3), Valia (within LS2 and 4) and Tadkeshwar (within LS1 and 3) mines of Cambay basin is bounded by two lignite seams (Figure 2). The fossiliferous units of Mangrol mine has been termed as shell bed (SB) 1, 2 and 3 from youngest to oldest. Umarsar, an extension of Panandhro mine of Ypresian Kutch basin (Figure 1c), preserving lignite units within Naredi Formation (Biswas 1992) also record similar stratigraphic succession, where the only fossiliferous unit (Unit 3) occurs in between two main lignite producing units (Unit 2 and 4) (Figure 3). Amber present throughout the succession. Preserved plant fossil is dominant in Unit 2 (Figure 3). A marine influence has been observed in the middle of an overall terrestrial lignite-bearing succession of the Ypresian Kutch and Cambay basins (Figures 2, 3).

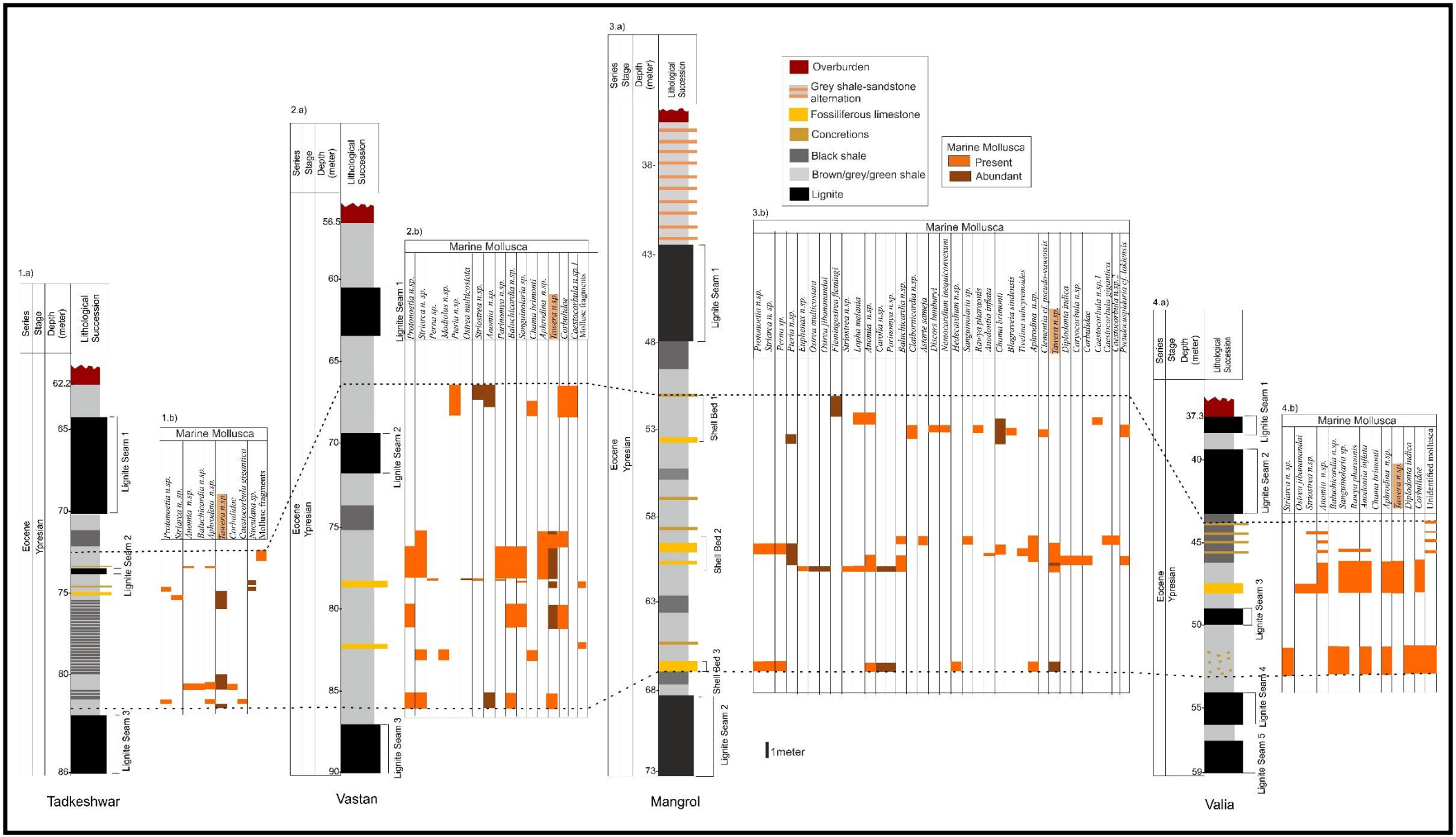

Figure 2. Lithostratigraphic columns of the four mine sections of Cambay basin and relative abundance of fossil bivalves from respective strata have been marked by colour in 1) Tadkeshwar 2) Vastan 3) Mangrol and 4) Valia lignite mine sections. The marine fossiliferous zone has been marked by dashed line.

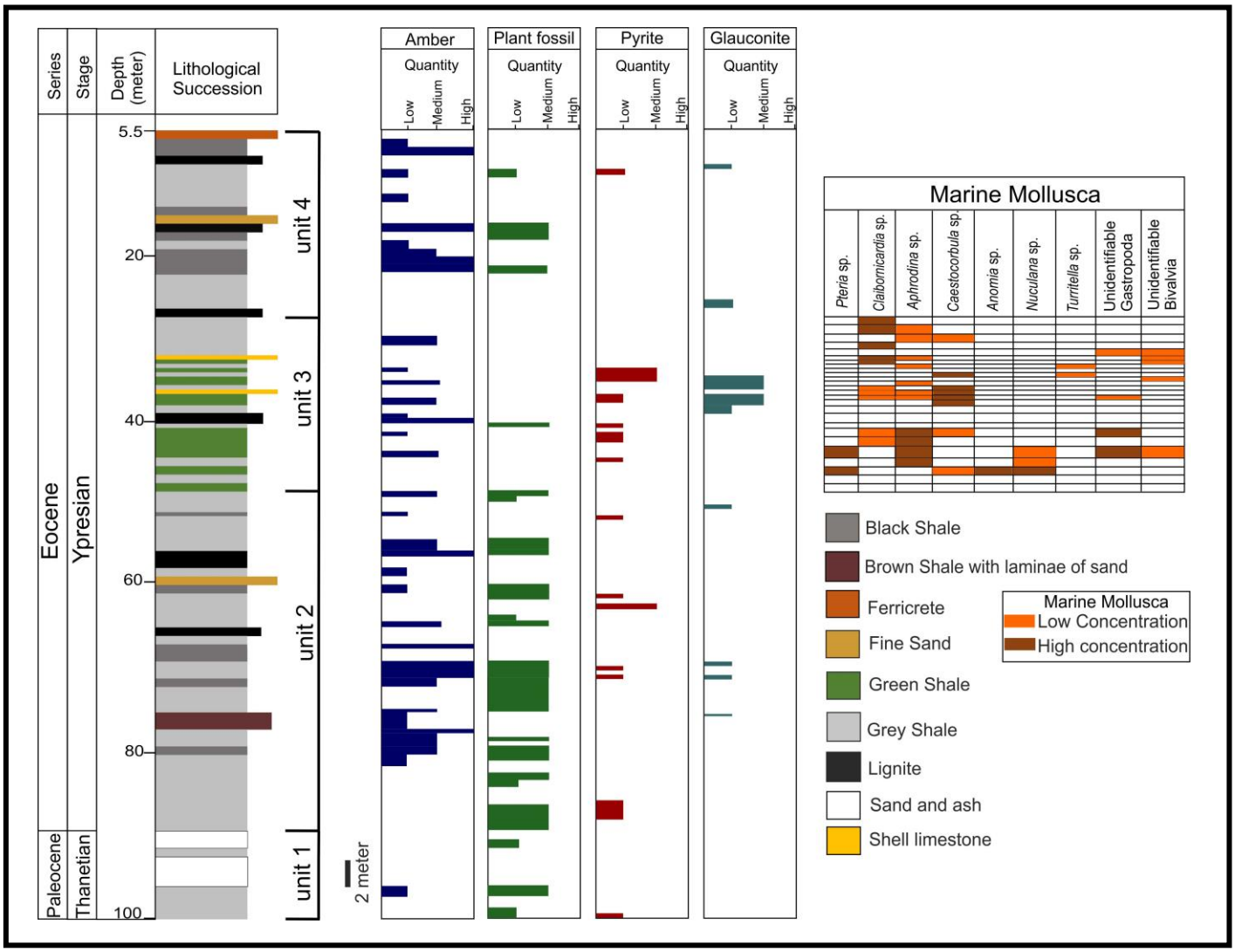

Figure 3. Lithostratigraphic section of the Umarsar mine as revealed from the drill-core. The four informal units of the succession are marked. Relative quantities of amber, plant matter, pyrite and glauconite in different levels are indicated. Relative abundance of mollusc fossils in different layers of unit 3 are demarcated.

B) Systematic Palaeontology

The fossils of this present study have been collected from the four lignite mines of Cambay basin, mostly from north and west face of Mangrol and south-west face of Vastan south pit. 31 bivalve species including 16 new, belonging to 30 genera including two new genera have been identified. Identification of two species were provisional due to insufficient morphological features.

Infraclass Pteriomorphia
Order Arcida
Superfamily Arcoidea
Family Noetiidae

Subfamily Noetiinae
Genus *Protonoetia*
Species *Protonoetia* n. sp. (PG/CB/P/Nt 1-146)
(Plate 1, Fig. 1)

Type Locality: Mangrol.

Type Horizon: SB2, SB3 of Mangrol.

Other Localities: In between LS3 and LS2 of Vastan and Tadkeshwar.

Diagnosis: Orthogyral to opisthogyral beak, fifteen teeth on both sides of beak, prosodetic ligament in juvenile, becoming amphidetic in later ontogeny; anterior muscle scar sub-triangular, posterior muscle scar sub-circular.

Subfamily Striarcinae
Genus *Striarca*
Species *Striarca* n. sp. (PG/CB/P/Nt 147-154)
(Plate 1, Fig. 2)

Type Locality: Mangrol.

Type Horizon: SB2, SB3 of Mangrol.

Other Localities: In between LS3 and LS2 of Vastan and Tadkeshwar, and between LS3 and LS4 of Valia.

Diagnosis: Shape trapezoidal, ventral margin oblique to dorsal margin, posterior margin longer than anterior margin; beak prosogral; amphidetic ligament throughout the dorsal margin; 14 and 25-27 teeth respectively in the anterior and posterior side of beak; costellete thick shell with 31 radial ribs; shell/ventral margin crenulated.

Order Mytilida
Superfamily Mytiloidea
Family Mytilidae
Subfamily Mytilinae
Genus *Perna*
Perna sp. (PG/CB/P/My 1-5)
(Plate 1, Fig. 3)

Locations: SB2, SB3 of Mangrol and in between LS3 and LS2 of Vastan.

Diagnosis: Shape trigonal, anteriorly pointed, posteriorly expanded; thin radial ornamentation, fine commarginal growth lines; shell boundary smooth; byssal gape along ventral margin.

Subfamily Modiolinae
Genus *Modiolus*
Species *Modiolus* n. sp. (PG/CB/P/My 6)
(Plate 1, Fig. 4)

Type Locality: Vastan mine.

Type Horizon: Above LS3.

Diagnosis: Modioliform, umbo not elevated, beak placed close to the anterior margin but not terminal; commarginal growth lines; a vaguely defined sulcus from posterior end of umbo to antero-ventral and postero-ventral junction.

Order Ostreida
Superfamily Pterioidea
Family Pteriidae
Genus *Pteria*
Species *Pteria* n. sp. (PG/CB/P/Pt 1-8)
(Plate 1, Fig. 5)

Type Locality: Mangrol.

Type Horizon: SB1 and SB2.

Other Localities: In between LS1 and LS2 of Vastan.

Diagnosis: Shape alate-trigonal, inner nacre layer; umbo placed near anterior margin but not terminal; dorsal margin straight; surface ornamented with commarginal ribs at regular interval.

Family Malleidae
Genus *Euphenax*
Species *Euphenax* n. sp. (PG/CB/P/Ma 1-5)
(Plate 1, Fig. 6)

Type Locality: Mangrol.

Type Horizon: SB2.

Diagnosis: Monomyarian bivalve with flat left valve, convex right valve; attachment scar absent; flat commissural shelf beyond the mantle cavity of right valve; beak incurved, opisthogyrous; postero-dorsal notch just behind ligamental groove in right valve; posterior adductor muscle oval to reniform in shape; surface of both the valves ornamented with radial ribs, left valve ribs fluted, bifurcated and possess wider interspaces than right valve.

Subfamily Striostreinae
Genus *Striostrea*
Species *Striostrea* n. sp. (PG/CB/P/Os 35-73)
(Plate 1, Fig. 7)

Type Locality: Mangrol.

Type Horizon: SB2 of Mangrol.

Other Localities: In between LS3 and LS1 of Vastan and between LS2 and LS3 in Valia.

Diagnosis: Medium sized shell with prominent mantle cavity; strongly opisthogyrous umbo; commarginal growth squamae on the external surface of left valve and right valve; prominent umbonal cavity; resilifer narrower than flat bourrelets.

Superfamily Ostreoidea
Family Ostreidae
Subfamily Ostreinae
Genus *Ostrea*
Species *Ostrea multicostata* Deshayes, 1832 (PG/CB/P/Os 1-34)
(Plate 1, Fig. 8)

Location: SB2 of Mangrol and in between LS3 and 2 of Vastan.

Discussion. The species has been ascribed to *Ostrea multicostata*, based on its medium size, higher than long shape, recurved umbo, absence of umbonal cavity in left valve, occasionally bifurcating thick radial ribs throughout left valve external surface, right valve with concentric commarginal threads, chomata being restricted to dorsal area only (Vredenburg 1928, Strougo 1976, El-Shazly et al. 2016).

Species *Ostrea jibananandai* Halder and Mitra, 2021 (PG/CB/Os 1-85)
(Plate 1, Fig. 9)

Type Location: Mangrol.

Type Horizon: Lower part of SB2.

Other Localities: In between LS2 and LS3 of Valia.

Diagnosis. Shells showing pronounced sexual dimorphism. Female shells large, attaining approximately 85 mm in height, relatively thin; distinctly higher than long; oblique. Strong shape modification occurring during ontogeny, from rounded in early juvenile stage to rather high in adulthood. Prominent umbonal cavity present in both valves. Left valve with anterior flange-like extension in dorsal part of the shell, providing settling space for dwarf male(s). Right valve with corresponding extension overarching dwarf male(s). Shell surface almost smooth, sometimes with blunt radial ridges on left valve and radial gashes on right valve. Dwarf male shells stunted, attaining approximately 20 mm in height, distinctly higher than long, attaching on inner surface of flange-like extension of left valves of females.

Genus *Lopha*
Species *Lopha melania* (Sowerby, 1840) (PG/CB/P/Os 74-76)
(Plate 1, Fig. 10)

Location: SB1 and SB2 of Mangrol.

Discussion: The present form has been ascribed to genus *Lopha* based on its small size, thin, corrugated shell, rounded plicae and prominent anachomata in postero-dorsal region (Dekker 2006).

Subfamily Flemingostreinae
Genus Flemingos*trea*
Species *Flemingostrea flemingi* d'Archiac & Haime, 1854 (PG/CB/P/Os 77-420)
(Plate 1, Fig. 11)

Location: Topmost part of SB1 at Mangrol mine.

Discussion: The left valve almost without any or with very small attachment scar, right valve flat in early growth stage, surface ornamented with regularly spaced concentric growth rings and adductor muscle scar of crescentic shape are the diagnostic characters (according to Hook 2010) to ascribe this taxon to *Flemingostrea flemingi*, the type species of the genus.

Order Pectinida
Superfamily Anomioidea
Family Anomiidae
Genus *Anomia*
Species *Anomia* n. sp. (PG/CB/P/An1-103)
(Plate 1, Fig. 12)

Type Locality: Mangrol.

Type Horizon: SB2 and SB3 of Mangrol.

Other Localities: Just above LS3 and below LS1 in Vastan and Tadkeshwar, and in between LS2 and LS3 of Valia.

Diagnosis. Very thin shell; left valve adductor muscle scar almost similar in size with posterior pedal retractor muscle scar and coalesced in some juvenile specimens; posterior byssal retractor muscle scar largest among the three scars; right valve with large open byssal foramen having height greater than length and ratio between 0.5 to 1; surface ornamented with very fine, closely spaced, wavy, continuous radial striae.

Genus *Carolia*
Species *Carolia* n. sp. (PG/CB/P/An104-150)
(Plate 1, Fig. 13)

Type Locality: Mangrol mine south face.

Type Horizon: SB3.

Diagnosis. Moderate shell size, small with respect to average size of the genus; surface ornamented with thin fluted radial striae, commarginal growth lines slightly frilled; right valve with closed byssal foramen in right valve.

Genus *Parinomya*

Species *Parinomya* n. sp. (PG/CB/P/An151-237)

(Plate 1, Fig. 14)

Type Locality: Mangrol mine south face.

Type Horizon: SB2 and SB3.

Other Localities: In Between LS2 and LS3 of Vastan.

Diagnosis: Thin but not translucent shell; left valve moderate to highly convex, right valve concave; posterior pedal retractor muscle scar the smallest and anterior adductor muscle scar the largest among the three scars of left valve; small circular byssal foramen, open to dorsal margin by a linear fissure; frills like strong commarginal growth lines giving the outer surface of both the valves a scaly appearance.

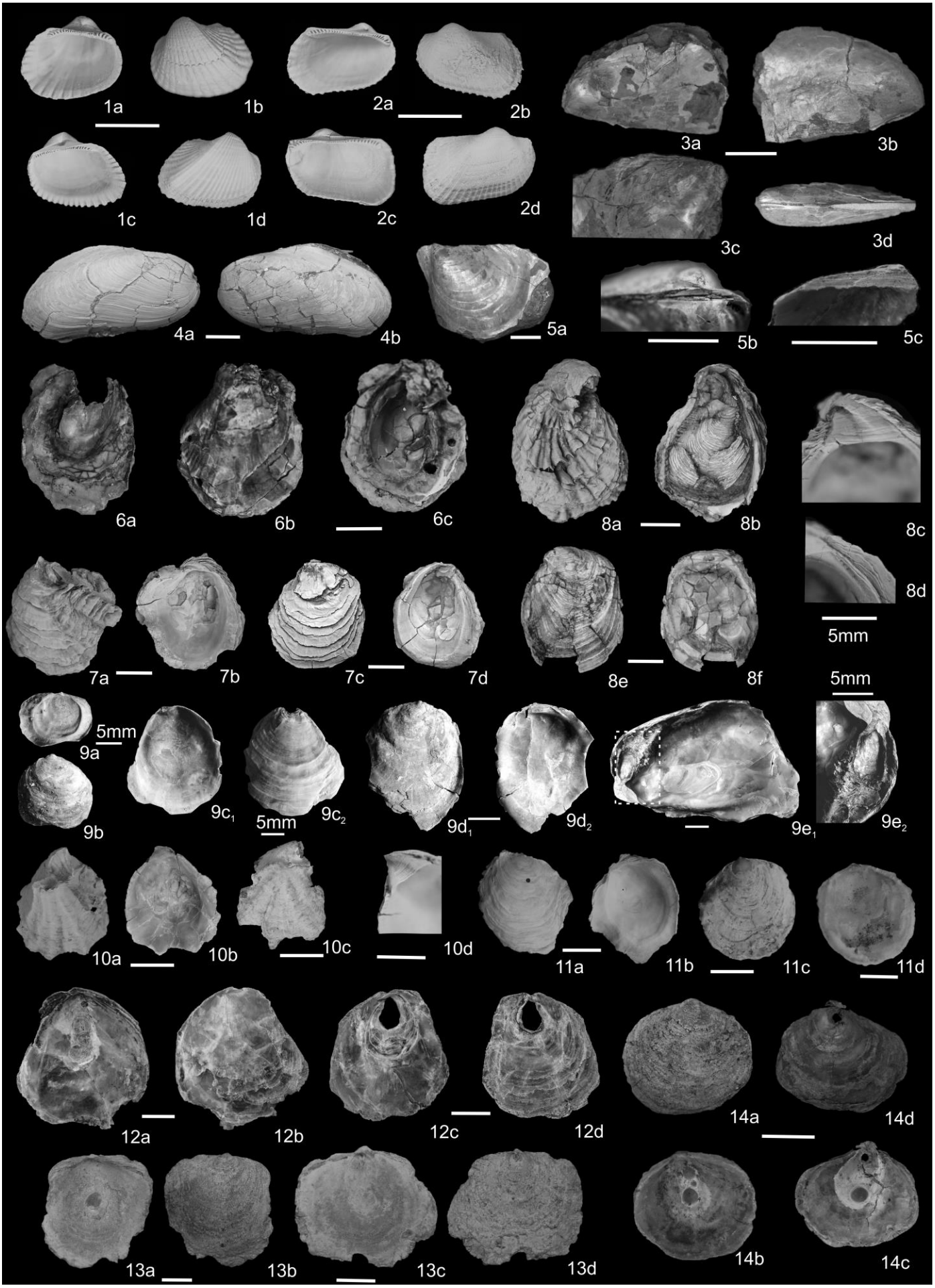
1a
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Plate 1.

Fig 1. *Protonoetia* n. sp. a) left valve internal and b) left valve external views of holotype PG/CB/P/Nt1 c) right valve internal and d) right valve external views of paratype PG/CB/P/Nt41.

Fig 2. *Striarca* n. sp. a) left valve internal and b) left valve external views of holotype PG/CB/P/Nt150 c) right valve internal and d) right valve external views of paratype PG/CB/P/Nt153.

Fig 3. *Perna sp*. a) left valve external b) right valve external c) terminal beak and d) dorsal views of PG/CB/P/My1.

Fig 4. *Modiolus n. sp*. a) right valve external b) left valve external and c) dorso-ventral views of holotype PG/CB/P/My6.

Fig 5. *Pteria* n. sp. a) left valve external b) hinge and c) left valve ligament of holotype PG/CB/P/Pt1.

Fig 6. *Euphenax* n. sp. a) left valve internal b) right valve external and c) right valve internal views of holotype PG/CB/P/Ma1.

Fig 7. *Striostrea* n. sp. a) left valve external and b) left valve internal views of holotype PG/CB/P/Os49; d) right valve external and e) right valve internal views of paratype of PG/CB/P/Os69.

Fig 8. *Ostrea multicostata* a) left valve external and b) right valve external view of PG/CB/P/Os2 c) resilium and d) catachomata of PG/CB/P/Os2 e) right valve external and f) right valve internal view of PG/CB/P/Os19

Fig 9. *Ostrea jibananandai*. a. PG/CB/Os 41a, paratype, juvenile, left valve, internal view, b) PG/CB/Os 39, right valve, juvenile, external view, c) PG/CB/Os 36, paratype, juvenile, d) PG/CB/Os 34, right valve of a specimen at mid-ontogeny, external (d1) and internal (d2) views; g1) PG/CB/Os 47, holotype, left valve of a carrying female, internal view; g2) detail showing left valve of an attached male.

Fig 10. *Lopha melania* a) left valve external and b) left valve internal view of PG/CB/P/Os74 c) left valve internal view of PG/CB/P/Os75 d) close up view of resilium of left valve of PG/CB/P/Os74.

Fig 11. *Flemingostrea flemingi* a) left valve external and b) left valve internal views of PG/CB/P/Os204 c) right valve external and d) right valve internal views of PG/CB/P/Os207.

Fig 12. *Anomia* n. sp. a) left valve internal b) left valve external and c) right valve internal and d) right valve external views of holotype PG/CB/P/An1.

Fig 13. *Carolia* n. sp. a) left valve internal b) left valve external c) right valve internal and d) right valve external views of holotype PG/CB/P/An104.

Fig 14. *Parinomya* n. sp. a) left valve internal b) left valve external c) right valve internal and d) right valve external views of holotype PG/CB/P/151.

Scale 10mm.

Infraclass Heteroconchia
Subterclass Archiheterodonta
Order Carditida
Superfamily Carditoidea
Family Carditidae
Subfamily Veneriardiinae
Genus *Baluchicardia*
Species *Baluchicardia* n. sp. (PG/CB/P/Ct 1-550)
(Plate 2, Fig. 1)

Type Locality: Mangrol.

Type Horizon: SB2 of Mangrol;

Other Localities: Between LS3 and 2 of Vastan, LS3 and 4 of Valia and LS3 and 2 of Tadkeshwar.

Diagnosis: Juveniles sub-circular, adults sub-quadrate in shape; hinge plate large, triangular, 3a-3b divergent, 3a distinct, thin, 3b very large, triangular, 5b laminar, nearly parallel to postero-ventral margin, PI distinct at ventral end of 5b; 2 pyramidal, 4b long, only slightly curved, AII slightly elongated, elevated just below lunule; 22-25 wide tripartite ribs, middle portion elevated.

Genus *Claibornicardia*
Species *Claibornicardia panchomi* n. sp. (PG/CB/P/Ct 650-850)
(Plate 2, Fig. 2)

Type Locality: Mangrol.

Type Horizon: Lower part of SB1.

Diagnosis: Sub-circular in shape, height greater than length; posteriorly inclined 2 and long curved 4b, A-II as extension of lunule margin, hinge of right valve with strong, triangular, slightly curved 3b and sharp, long 5b, 3a thin, only slightly elevated, posteriorly inclined, P-I small, near ventral margin of 5b; weakly tripartite radial ribs, spines on rib crests, fifth rib from posterior end weak and depressed.

Superfamily Crassatelloidea
Family Astertidae
Genus *Astarte*

Species *Astarte* n. sp. (PG/CB/P/At 1,2)
(Plate 2, Fig. 3)

Type Locality: Mangrol.

Type Horizon: SB2.

Diagnosis: Shell small, subequilateral, inflated; surface with bipartite commarginal ribs in early ontogeny, later ontogeny marked with tripartite ribs, ribs weak and blunt near venter.

Subterclass Euheterodonta
Superorder Imparidentia
Order Cardiida
Superfamily Cardioidea
Family Cardiidae
Subfamily Protocardinae
Genus *Discors*
Species *Discors bunburyi* (d'Archiac & Haime, 1854) (PG/CB/P/Cd1)
(Plate 2, Fig. 4)

Location: SB1 of Mangrol.

Discussion: This form from the Cambay basin is considered as *D. bunburyi* because of its oblique postero ventrally projected shell, almost parallel anterior and posterior margins, sloping postero ventral margin and well defined lunule and escutcheon.

Genus *Nemocardium*

Species *Nemocardium inaequiconvexum* (Cossmann and Pissarro, 1927) (PG/CB/P/Cd 2-4)

(Plate 2, Fig. 5)

Location: SB1 of Mangrol mine north face.

Discussion: Based on shape and size, number of ribs, posterior ribs being stronger than anterior ones, and almost smooth anterior region, this taxon has been ascribed to *N. inaequiconvexum.*

Genus *Hedecardium*
Species *Hedecardium* n. sp. (PG/CB/P/Cd5)
(Plate 2, Fig. 6)

Type Locality: Mangrol.

Type Horizon: SB3.

Diagnosis: Shell large; large, weakly demarcated lunule, and long, narrow escutcheon demarcated by ridge; ligament opisthodetic; 42 flat-topped, wide radial ribs, rib demarcating posterior slope prominent, minute beads present on ribs, 3-4 ribs narrower on the posterior slope, anterior gape present.

Superfamily Tellinoidea
Family Psammobiidae
Genus *Sanguinolaria*
Sanguinolaria sp**.** **(**PG/CB/P/Ps1)
(Plate 2, Fig. 7)

Locality: SB2 of Mangrol mine, in between LS3 and LS2 of Vastan and LS2 and LS4 of Valia mine.

Discussion: The elongate equivalve shells, rounded anterior margin, almost central umbo, shallow posterior gape and concentric sculpture are the external morphologic characters to ascribe this form to Psammobiidae family (according to Moore 1969; Willan 1993; Coan and Valentich-Scott 2012). Based on the trapezoidal shape, inflated nature, extended posterior side and small siphonal gape, this has been considered as a member of the genus *Sanguinolaria* Lamarck, 1799 (according to Moore 1969; Roth and Guruswamy-Naidu 1974; Coan and Valentich-Scott 2012). Neither it could not be ascribed to an known species, nor erected as a new species based on the only one specimen, that too an internal mould without any preserved internal morphologic features.

Order Lucinida
Superfamily Lucinoidea
Family Lucinidae
Subfamily Leucosphaerinae
Genus *Anodontia*
Species *Anodontia inflata* (d'Archiac and Haime 1854) (PG/CB/P/Lu2)
(Plate 2, Fig. 8)

Location: SB2 of Mangrol mine south-west face, in between LS2 and LS4 of Valia.

Discussion. Globular, nearly inequilateral shell, straight posterior boundary giving the shell a square appearance and concentric fine folds are the features to ascribe this form to the *Lucina inflata* d'Archiac and Haime, 1854 from Pakistan. Smooth surface except round commarginal folds, occasionally fine radial lines, lacking hinge teeth and inconspicuous lunule are the identifying morphological characters for *Anodontia* (Taylor and Glover, 2006). Based on these features, this species has been ascribed to *Anodontia* genus.

Subfamily Pegophyseminae
Genus *Rawya*
Species *Rawya pharaonis* (Bellardi, 1851) (PG/CB/P/Lu1)
(Plate 2, Fig. 9)

Location: SB1 of Mangrol mine north face, in between LS2 and LS3 of Valia.

Discussion: Small beak, surface ornamentation of low rounded commarginal ridges, fine concentric commarginal lines and radial ribs of moderate strength, sub-rounded shape are the diagnostic morphological features to ascribe this form to *Rawya pharaonis* (Cox 1931b).

Order Venerida
Superfamily Chamoidea
Family Chamidae
Genus *Chama*
Species *Chama brimonti* d'Archiac and Haime, 1854 (PG/CB/P/Ch1-110)
(Plate 2, Fig. 10)

Locality: Lowermost level of SB1 and a few in SB2 of Mangrol mine; beyween LS1 and LS2 of Vastan mine.

Discussion: The present form is ascribed to *C. brimonti* because of its rhombic, higher than long shell with characteristic foliaceous ornamentation containing spines.

Superfamily Veneroidea
Family Veneridae
Genus *Blagraveia*
Species *Blagraveia sindensis* (d'Archiac and Haime, 1854) (PG/CB/P/Ve 122-123)
(Plate 2, Fig. 11)

Locality: SB1 in Mangrol mine north face.

Discussion: This form has been ascribed to the *B. sindensis* (d'Archiac & Haime, 1854) based on its overall shape and size. Bhatia & Khosla (1978) considered *B. corrugata* (Cox, 1931b) conspecific to *B. sindensis,* based on its similar lunule, escutcheon and ornamentation despite a more anteriorly elongated shape of *B. corrugata*.

Subfamily Meretricinae
Genus *Tivelina*
Species *Tivelina subcyrenoides* (d'Archiac and Haime 1854) (PG/CB/P/Ve 33, 34)
(Plate 2, Fig. 12)

Locality: Lowermost greenshale of SB2 in Mangrol mine south-west face.

Discussion: This form has been ascribed to *T. subcyrenoides,* reported from the Upper Kirther Shales of Pakistan, based on its shape, concentric growth lines, cordiform lunule and deep escutcheon.

Subfamily Pitarinae
Genus *Aphrodina*
Species *Aphrodina* n. sp. (PG/CB/P/Ve1-32, 100-110)
(Plate 2, Fig. 13)

Type Locality: Mangrol.

Type Horizon: SB3 and SB2 of Mangrol.

Other localities: In between LS3 and LS2 of Vastan, Valia and Tadkeshwar, and LS3 and LS4 of Valia.

Diagnosis: Three cardinal teeth in right valve and two cardinal teeth in left valve, 3b bifid; indistinct escutcheon, prominent lunule; deep, tongue shaped pallial sinus with a 'v' shaped extension towards beak.

Subfamily Clementiinae
Genus *Clementia*
Species *Clementia cf. pseudoyawensis* (Iqbal, 1969b) (PG/CB/P/Ve 121)

(Plate 2, Fig. 14)

Locality: SB1 in Mangrol mine south-west face.

Discussion: *C. pseudo-yawensis* (Iqbal 1969b) from the Middle Eocene of Pakistan has the maximum resemblance with this form in having a sub-rectangular outline, irregularly spaced commarginal ornamentation and ill-defined lunule.

Genus new genus
Species new species (PG/CB/P/Ve 35-99)
(Plate 2, Fig. 15)

Type Locality: Mangrol mine.

Type Horizon: SB3 and SB2.

Other Localities: In between LS3 and LS2 of Vastan and Tadkeshwar.

Diagnosis: Small, subcircular in shape; three cardinals in each valve, 4b anteriorly and 3b posteriorly split; small shallow pallial sinus; commarginal growth lines and annual growth increments.

Superfamily Ungulinoidea
Family Ungulinidae
Genus *Diplodonta*
Species *Diplodonta indica* (d'Archiac and Haime 1854) (PG/CB/P/Un1,2)
(Plate 2, Fig. 16)

Locality: SB2 in Mangrol mine south-west face.

Discussion: This form has been ascribed to *Diplodonta indica* (d'Archiac & Haime 1854) based on its overall size, high posterior and narrow anterior sides, and the morphological features such as thin shell, nearly centrally placed umbo, prosogyral beak, absence of lunule, clearly defined lanceolate escutcheon and irregularly spaced commarginal ridges.

Order Myida
Superfamily Myoidea
Family Corbulidae
Genus *Caryocorbula*

Species *Caryocorbula* n. sp. (PG/CB/P/Co1-50)

(Plate 1, Fig. 17)

Type Locality: Mangrol.

Type Horizon: SB2.

Diagnosis: Subquadrate shape, right valve more inflated than left valve; straight postero-dorsal margin; commarginal ribs oblique in posterior slope; absence of lunule and escutcheon; wide gape in posterior boundary.

Genus new genus

Species new species (PG/CB/P/Co51-70)

(Plate 1, Fig. 18)

Type Locality: Mangrol mine.

Type Horizon: SB2.

Other Localities: In between LS2 and LS3 of Tadkeshwar, LS1 and LS3 of Vastan and LS2 and LS4 of Valia.

Diagnosis: Nearly equivalve shell, inequilateral, posteriorly rostrate; right valve slightly more inflated and overlapping left valve; right valve having slightly opisthogyral and left valve having orthogyral beaks; lunule and escutcheon demarcated by conspicuous ridges in left valve, faint in right valve; weak internal groove of right valve to receive left valve; right valve hinge having one wedge-like cardinal and two thin lateral teeth; left valve having one ridge on the dorsal side of chondrophore; surface ornamented with very close spaced commarginal growth lines and somewhat irregularly spaced commarginal ribs, right valve having faint radial lines in the central region.

Superorder Anomalodesmata

Superfamily Cuspidarioidea

Family Cuspidariidae

Genus *Pseudocuspidaria*

Species *Pseudocuspidaria cf. lakiensis* Cox, 1938 (PG/CB/P/Cu 1-16)

(Plate 2, Fig. 19)

Locality: SB1 and SB2 in Mangrol mine.

Discussion: The overall shape and morphometric parameters of the Cambay samples are closely comparable with the Laki forms. Hinge features and other internal characters of the species is not known. Based on the nearly identical external morphological features and discovery from the contemporaneous early Eocene beds, it has been considered as a member of *P. lakiensis*.

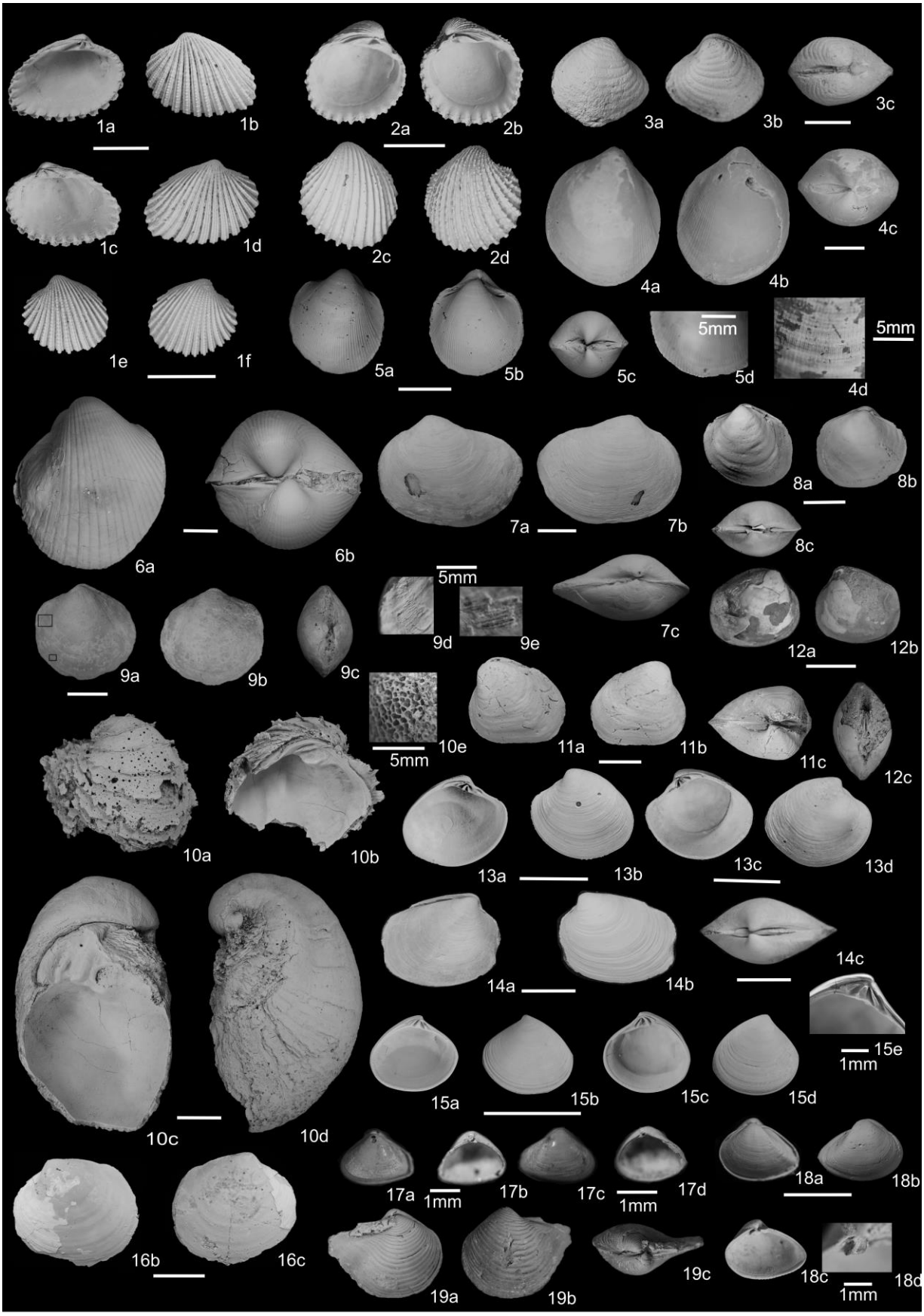

Plate 2.

Fig 1. *Baluchicardia* n. sp. a) left valve internal and b) left valve external views of adult holotype PG/CB/P/Ct601; c) right valve internal and d) right valve external views of adult paratype PG/CB/P/Ct600; e) juvenile left valve external view of PG/CB/P/Ct602 f) juvenile right valve external view of PG/CB/P/Ct603.

Fig 2. *Claibornicardia* n. sp. a) left valve internal and b) left valve external views of holotype PG/CB/P/Ct802; c) right valve internal and d) right valve external views of paratype PG/CB/P/Ct801.

Fig 3. *Astarte* n. sp. a) right valve b) left valve and c) dorsal view of holotype PG/CB/P/At1.

Fig 4. *Discors bunburyi* a) left valve b) right valve c) dorsal and d) close up view of surface ornamentation of PG/CB/P/Cd1.

Fig 5. *Nemocardium inequiconvexum* a) left valve b) right valve c) dorsal and d) close up view of surface ornamentation and posterior crenulated margin of PG/CB/P/Cd4.

Fig 6. *Hedecardium* n. sp. a) right valve external and b) dorsal views of holotype PG/CB/P/Cd5.

Fig 7. *Sanguinolaria sp.* a) left valve external b) right valve external and c) dorsal views of PG/CB/P/Ps1.

Fig 8. *Anodontia inflata* a) left valve b) right valve and c) dorsal view of PG/CB/P/Lu2.

Fig 9. *Rawya pharaonis* a) left valve b) right valve c) dorsal and d) close up view of (a, larger box) radial surface ornamentation and e) (b, smaller box) commarginal surface ornamentation of PG/CB/P/Lu1.

Fig 10. *Chama brimonti* a) left valve external and b) internal views of PG/CB/P/Ch22; c) left valve internal and d) right valve external views of PG/CB/P/Ch75 e) honeycomb structure observed from abraded shell surface of PG/CB/P/Ch42.

Fig 11. *Blagraveia sindensis* a) left valve b) right valve and c) dorsal view of PG/CB/P/Ve123.

Fig 12. *Tivelina subcyrenoides* a) right valve b) left valve and c) dorsal view of PG/CB/P/Ve34.

Fig 13. *Aphrodina* n. sp. a) left valve internal and b) left valve external views of holotype PG/CB/P/Ve3; c) right valve internal and d) right valve external views of paratype PG/CB/P/Ve14.

Fig 14. *Clementia cf. pseudo-yawensis* a) right valve b) left valve and c) dorsal view of PG/CB/P/Ve121.

Fig 15. New genus (Veneridae family) a) left valve internal and b) left valve external views of holotype PG/CB/P/Ve1 c) right valve internal and d) right valve external views of paratype PG/CB/P/Ve47.

Fig 16. *Diplodonta indica* a) dorsal b) left valve and c) right valve view of PG/CB/P/Un1.

Fig 17. *Caryocorbula* n. sp. a) left valve external view of holotype PG/CB/P/Co1 b) left valve internal view of paratype PG/CB/P/Co2 c) right valve external view of holotype PG/CB/P/Co1 d) right valve internal view of paratype PG/CB/P/Co3.

Fig 18. New genus (Corbulidae family) a) left valve external and b) right valve external views of holotype PG/CB/P/Co51 c) right valve internal and d) chondrophore of right valve in paratype PG/CB/P/Co52.

Fig 19. *Pseudocuspidaria cf. lakiensis* a) right valve b) left valve and c) dorsal view of PG/CB/P/Cu16

Scale 10mm.

C) Early Eocene Hyperthermal and Transgressive events

1. Material and Methods: The present study is based on a drill core from the Umarsar mining area (23º43′23″N, 68º50′03″E) of Kutch basin and systematically collected samples from the west face of the Mangrol mine (21°26′50″N, 73°07′45″ E) in Cambay basin (Figure 1). The Total Organic Carbon (TOC) (%) and $\delta^{13}C_{org}$ values were measured from rock samples, collected at about 1m interval from the mine and drill core sections. $\delta^{13}C_{carb}$ and $\delta^{18}O_{carb}$ are also obtained from bulk carbonate from the fossil molluscs of Mangrol mine. Temperature was calculated based on the $\delta^{18}O_{carb}$ values.

2. Results and Discussion: The average value of the obtained $\delta^{13}C_{org}$ is about -27.5‰ with a standard deviation of 0.72‰ (1σ, n= 40) from Mangrol mine and -26.87‰ with the standard deviation of 0.56‰ (1σ, n= 103) from Umarsar mine. The calculated temperature range within SB1 to 3 of Mangrol is within 30.84°C to 37.74°C during Ypresian. Five negative carbon isotope excursions (CIE) representing hyperthermal events have been recognized from both the basins, where the oldest one has the highest magnitude (Figure 4.1b,2b). Based on the relative positions and magnitudes of CIEs, the hyperthermals have been identified as PETM, ETM2/H1, H2, I1 and I2 from the oldest to youngest (Figure 4.1b,2b). The presence of lignite seams and reports of aracaceae and mangrove spore-pollens from the Cambay shale unit (i.e within Vastan lignite mine) and Panandhro-Umarsar lignite mines of Kutch basin indicate a marginal marine terrestrial setting during the early Eocene. Marine fossil bearing stratigraphic units in the middle of the successions represent marine incursion in these coastal basins. The most prominent marine incursion has been recorded from the vicinity of ETM2 and H2 in both the mines of Mangrol and Umarsar (Figures 2, 3, 4.1a,2a). A thin fossiliferous unit (SB3) is present just above the PETM peak in Mangrol mine (Figure 2a,b) indicating marine incursion, while no such marine signature is present in Umarsar, concomitant to PETM (Figure 3). Previous studies support this observation because they record PETM within lignite and carbonaceous shale units in the western coast basins of India, whereas ETM2 coincides with a marine interval (Clementz et al., 2011; Khozyem et al., 2021). Records from North Sea basin of Europe, and Fushun of China depict a gradual change from terrestrial to marine environment after PETM (Chen et al., 2014; Lenz et al., 2021 and

references therein). Global mean sea level (GMSL) curve (Kominz et al., 2008; Miller et al., 2020) reveals a sharp increase in the sea level succeeding P-E boundary at 56 Ma and a higher sea level at ~54Ma during ETM2-H2 than that near the P-E boundary. Therefore, the higher sea level during ETM2-H2 (than during PETM) was primarily reflected in the coastal inland basins of western India as marine fossil bearing levels (Figures 2, 3). The co-occurrence of transgression and the pair of hyperthermals ETM2-H2 strongly suggests their causal link. This aspect has never been explored in literature. There is only one report of a transgression possibly associated with ETM2 (Sluijs et al. 2008). However, a higher sea level during ETM2 and H2 (Kominz et al., 2008; Miller et al., 2020) unequivocally suggests the global nature of this phenomenon. The relative position of Umarsar and Mangrol with respect to the sea may be responsible for the difference in marine influence associated with PETM.

The main fossiliferous part, concurrent to ETM2-H2 in both the basins house eurytopic estuarine bivalves (Ostridae, Anomiidae) in the basal part. The middle part of the fossiliferous zone of Mangrol houses abundance of pro-delta, shoreface to offshore preferring bivalves (i.e Carditidae, Chamidae). And the uppermost part is densely populated by estuarine bivalves like *Flemingostrea flemingi* (Figure 2). So, a progressive transgression with the onset of ETM2, followed by a regression after H2 has been observed.

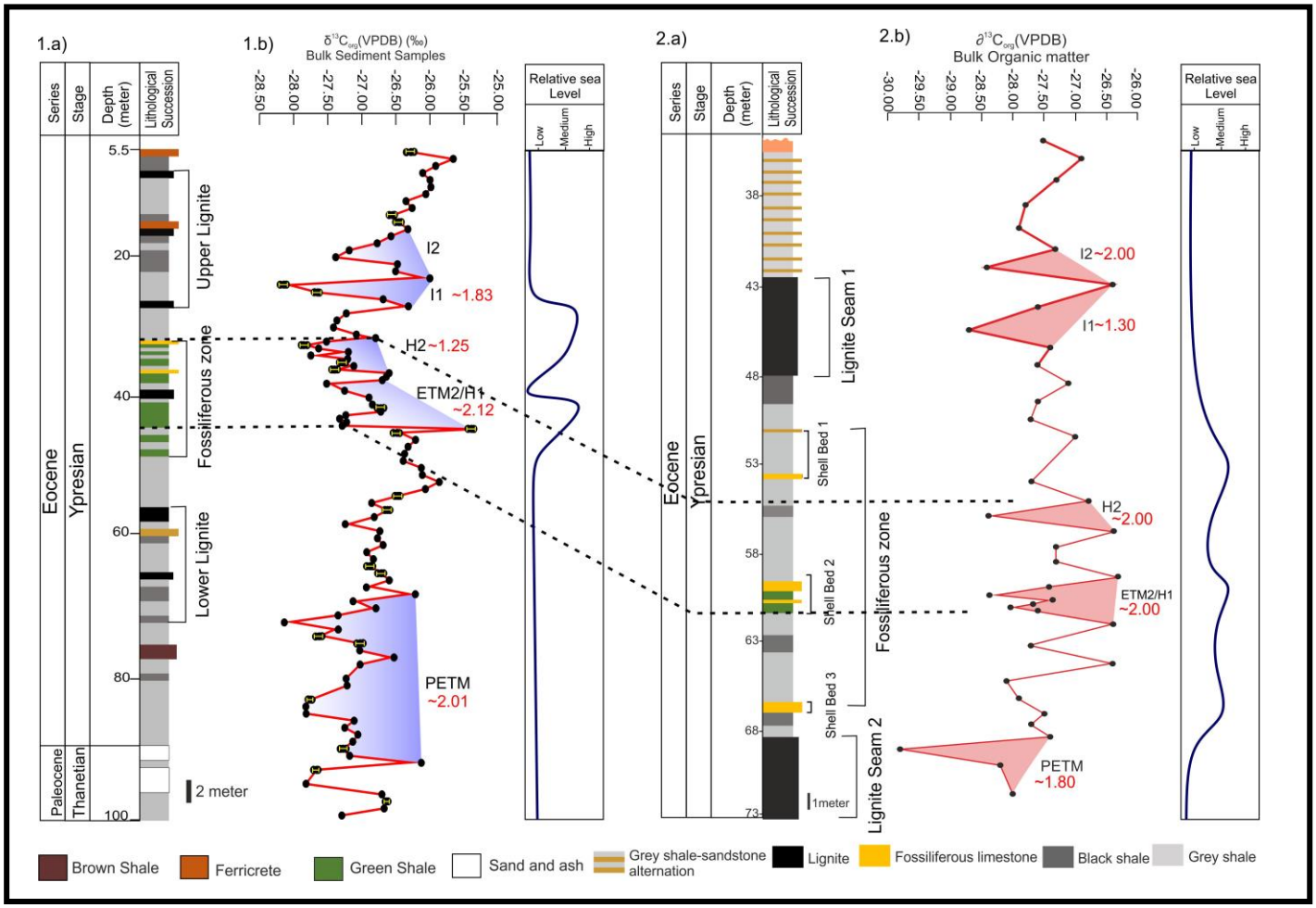

Figure 4. Litho- and isotope stratigraphic columns of Umarsar and Mangrol mines along with relative sea level curves 1.a) Lithostratigraphic section of the Umarsar open pit mine. 1.b) stable organic carbon isotope curve, obtained from bulk sediment samples of Umarsar; 1.c) relative sea level curve of Umarsar mine section. 2.a) Lithostratigraphic section of the Mangrol open pit mine; 2.b) stable organic carbon isotope curve, obtained from bulk sediment samples of Mangrol; 2.c) relative sea level curve of Mangrol mine section.

D) Bivalves' Response: Diversity, Life Mode, Environment

1. Life mode and environmental preference

Noetiidae: The equant juveniles of *Potonoetia* n. sp. retain the character of their free-living ancestors and became byssally attached on attaining adulthood. The extension of ligament from anterior to posterior region and orthogyral to slightly opisthogyral beak also aid in their epifaunal byssate living habit (Plate 1, fig. 1). Reduced and round anterior boundary, straight posterior boundary, prosogyral beak, non-parallel hinge plate and ventral margin indicate shallow infaunal nature of *Sriarca* n. sp. (Plate 1, fig. 2), where the straight ventral margin lies just below the sediment water interface. Both of these species have been reported from estuarine to offshore regions.

Ostreidae: Diverse oysters have been found in marginal marine setting as opportunist taxa, where competing co-occurring organisms are few due to unfavourable conditions (Bayne, 2017).

Facultative monogamy of *Ostrea jibananandai*:

Most of the larger females of *O. jibananandai* Halder, 2021, reported from the base of ETM2 (~54.09Ma) of the Cambay Basin (Figure 2), carry only one dwarf male each in the anterior extension of their left valves (Plate 1, fig. 9). This phenomenon has also been observed in the extant *O. puelchana* d'Orbigny, 1842 (Pascual et al., 1989) and *O. alvarezii* from possible upper Pliocene (2.5–3 Ma) rocks of Argentina (Iribarne et al., 1990). This report extends the antiquity of the carrying phenomenon in *Ostrea* lineage by about 50 Ma. In the *Ostrea* species characterized by the females carrying dwarf males at their hinges, sperms from only the males would fertilize all eggs of the host females. This increases the success of fertilization by reducing uncertainty involved in the spermcasting process. Sedimentation started in the coastal restricted setting of the Cambay basin in the lower Paleogene in response to increasing temperature and transgression. The basin possibly experienced ocean acidification and hypoxia along with an increase in temperature. These factors, independently or in concert, must have put significant stress on the oyster's physiological activities. Gametogenesis along with sex ratio, and/or sperm motility were likely to be seriously affected. In a possible attempt to optimize reproduction in this perturbed environment females acted as hosts to dwarf males.

Anomiidae*:* Anomiids successfully colonised in marginal marine brackish environment from late Jurassic onwards (Fürsich and Werner 1989).

Carditidae: *Venericardia* are so abundant in the Eocene of Gulf Coastal Plain and Atlantic Coast of America that Heaslip (1968) described its' members as the guide fossil of Paleogene. Carditida, especially the Cenozoic forms are infaunal suspension feeder, residing just beneath the water-sediment interface in pro-delta to deep subtidal shelf (McClure and Lockwood, 2015; Perez, 2019).

The juveniles of *Baluchicardia* n. sp. having rounded outline were free-living, whereas adults with shorter anterior margin, straight ventral margin and elongated postero-ventral region became endo-

byssate. The longer and stronger posterior cardinals 3b, 4b and 5b, and relatively weaker right valve anterior 3a (Plate 2, fig. 1) are direct consequences of this life habit (Heinberg, 1993).

Strong 3b, long 5b, 4b and weaker 2, 3a, weak tripartite ribs and strong spines on surface of *Claibornicardia* n. sp. (Plate 2, fig. 2) depict their shallow infaunal nature where the gently round outline aided in burrowing.

Chamidae: *Chama* is a stenohaline (Pastorino 1991), shallow water (Stanley 1970) form getting cemented in neologic stage, either by right or left valve to a hard substrate (Yonge 1967; Coan and Valentich-Scott 2012). A hyperthermal event has been noticed just prior to the Shell Bed 1 of Mangrol mine (Figure 3), where abundance of *Chama* has been observed. The spines of *C. brimonti* not only help the fauna to attach themselves strongly to the substratum but also work as a sensory organ.

Veneridae: The relatively smooth shells of *Aphrodina* (Plate 2, fig. 13) and round shape of new genus (Veneridae family) (Plate 2, fig.14) provide ease for rapid burrowing. Both of *Aphrodina* and *Tivelina* have large pallial sinus, which indicate a larger siphon in order to collect food from suspension. Venerids are residents of lagoonal to offshore marine environment.

Corbulidae: Sluggish burrowing Corbulids are residents of nearshore, fine-grained sediments deposited in relatively low-energy environments in normal marine to brackish waters. Monotypic shell beds of corbulids associated with brackish-water conditions are known (Lewy & Samthleben 1979).

2. Bivalves' response to environmental change:

a) Cambay Basin: The middle part of the mine sections in Cambay basin, bounded by lignite seams on top and bottom, bear signatures of marine influence (Figure 2). The sections of Vastan and Mangrol initiate with abundance of Oysters and Anomiids (Figure 2b,c). *Flemingostrea* n. sp. forms a bank at its top in Mangrol whereas *Anomia* n. sp. and *Striostrea* n. sp. dominate the upper part of Vastan (Figure 2b,c). Monospecific shell beds of new genus (Veneridae family) just preceding or concurring the *Anomia*-dominated base is also a common feature in all the mines (Figure 2). Estuarine-bivalve-dominated bottom and top of this marine sequence reflect the incoming and retreating sea in this sheltered basin, when fluctuations in its physico-chemical conditions were at its

maximum. Increase in marine influence in the intervening portion supported a relatively more diverse fauna and eliminated oysters. In this sheltered habitat, however, a few opportunist taxa prevailed even with relatively high marine influence. The taxa include bivalves like Carditidae, Corbulidae, Veneridae and Chamidae. Some of these, including *Baluchicardia* n. sp. and new genus (Veneridae family), forming thin almost monospecific shell concentrations with negligible shell breakage in Mangrol, Vastan and Tadkeswar mine sections, indicate extremely quiet depositional condition with slow sedimentation rate in the restricted part of the basin. White shell carbonates composed of micrite and fragmentary mollusc shells that had been identified as representing maximum flooding surfaces in the Vastan mine (Prasad et al., 2013) are a product of relatively high energy. Specific and generic composition of the marine mollusc fauna got modified to a certain extent in the time spent between the deposition of the two shell beds of Mangrol mine. Sea finally retreated from this restricted part of the Cambay basin after the deposition of the oyster bank in Mangrol and *Anomia* and *Striostrea* in Vastan at the top of shell beds.

b) Umarsar Mine: The green shale part (Unit 3) is dominated by bivalves (Figure 3). A species of *Anomia* (family Anomiidae), along with *Pteria* sp. (family Pteriidae), are the most common forms in the lowermost part (Figure 3). They are quickly followed up the sequence by members of Corbulidae (*Caestocorbula* sp.) and Carditidae (*Claibornicardia* sp.). *Caestocorbula gujaratensis* Halder & Bano, 2015 and members of Carditidae (*Baluchicardia* and *Claibornicardia*) are also common in the early part of the marine mollusc bearing green shale layers of the Naredi Formation (Banerjee et al., 2019). These eurytopic forms flourished in the marginal marine basin under low selection pressure. Other molluscs recorded from this interval are *Aphrodina* sp. (family Veneridae), *Nuculana* sp. (Family Nuculanidae) and the only identifiable gastropod *Turritella* (family Turritellidae), and some unidentifiable fragments (Figure 3). *Aphrodina* and *Nuculana* are shallow-burrowing, suspension-feeding bivalves living in soft-substratum shelf environment (Moussavou, 2015; Coan & Valentich-Scott, 2012). *Turritella* also prefers a similar habitat (Allmon, 1988). The first to disperse in this part of the basin were epibenthic bivalves from anomiid and pteriid lineages. Later, with the establishment of a quiet marine environment, shallow burrowing and suspension

feeding bivalves and gastropods dominated the area. However, the mollusc diversity remained low in this marginal marine environment.

E) Palaeobiogeography

1. Global distribution of Paleogene genera: A detailed palaeobiogeographic analysis of the Paleogene bivalves reveals important global changes in palaeoclimate and oceanic palaeocurrent induced by tectonic changes. Palaeobiogeographic provinces of the three Paleogene epochs have been established based on global distribution of bivalve genera by network and cluster analyses (Table 1; Figures 5, 6, 7). The study reveals important changes in palaeobiogeographic province architecture (Table 1), and latitudinal patterns of extinction and appearance of faunas through the epochs of the Paleogene (Figure 8.1,2). Yet, certain broad features of the distribution persisted through the Paleogene and certain modern features become established during this period.

The Northern Hemisphere had a higher faunal diversity and more numerous localities that housed bivalves than that of the Southern Hemisphere. Europe and North America in the Northern Hemisphere, and Australia, Argentina and New Zealand along with Antarctica in the Southern Hemisphere are the major areas that yielded most diverse faunas (Figures 5, 6, 7). The presence of extensive shallow shelves and epeiric basins in these areas, and prevalence of a more equable, warm climate in comparison to the present-day facilitated this general pattern of distribution of the Paleogene bivalves. The relationships between the Southern Hemisphere localities evolved through the Paleogene primarily with the modifications of oceanic palaeocurrents. The development of DP and TG in later part of the Eocene, resulting in the decimation of South Oceanic Gyre and establishment of Antarctic circumpolar current (ACC), are causally linked to the palaeobiogeographic evolution and connection between Argentina, Australia and New Zealand localities (Figures 6, 7). The generation of continental ice sheet in Antarctica due to the establishment of ACC during the Oligocene ultimately wiped off the bivalve fauna from Seymore Island (Figure 7).

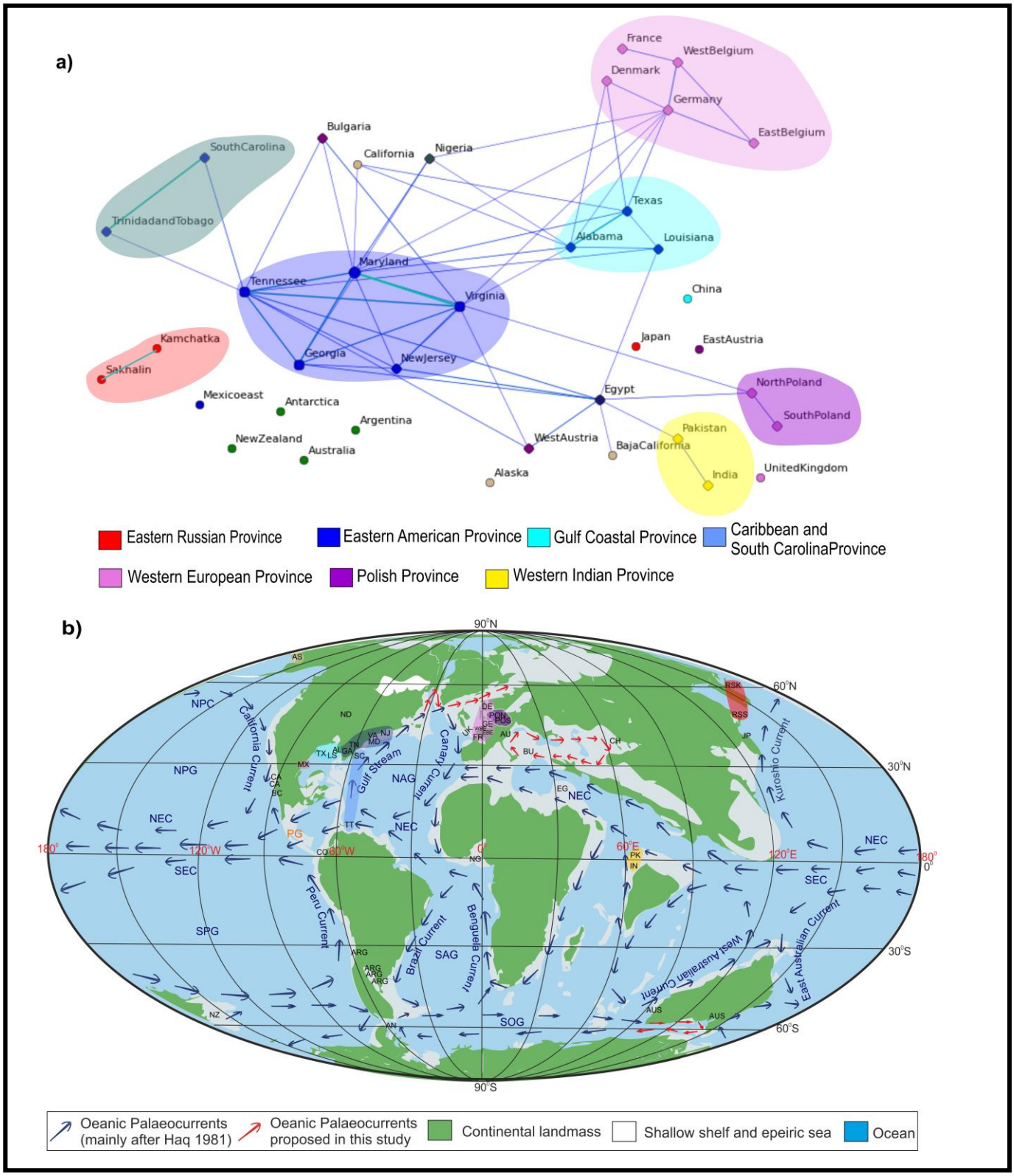

Figure 5. Palaeobiogeographic provinces defined by distinct colours a) in network analysis, performed in generic level of all the bivalves present in Paleocene (executed by EdeNetworks) b) palaeocoastline map of Paleocene (~60Ma) (Scotese et al. 2016).

A trans-Pacific palaeobiogeographic affinity between the eastern Asian and the western American provinces in the Northern Hemisphere prevailed through most of the Paleogene time (Figures 5b, 6b,7b). This indicates the presence of Northern Pacific Gyre (NPG) in the period. A trans-Atlantic

closeness between the eastern American and the western European basins is also documented indicating the presence of Northern Atlantic Gyre (NAG) (Figures 5b, 6b, 7b). The presence of

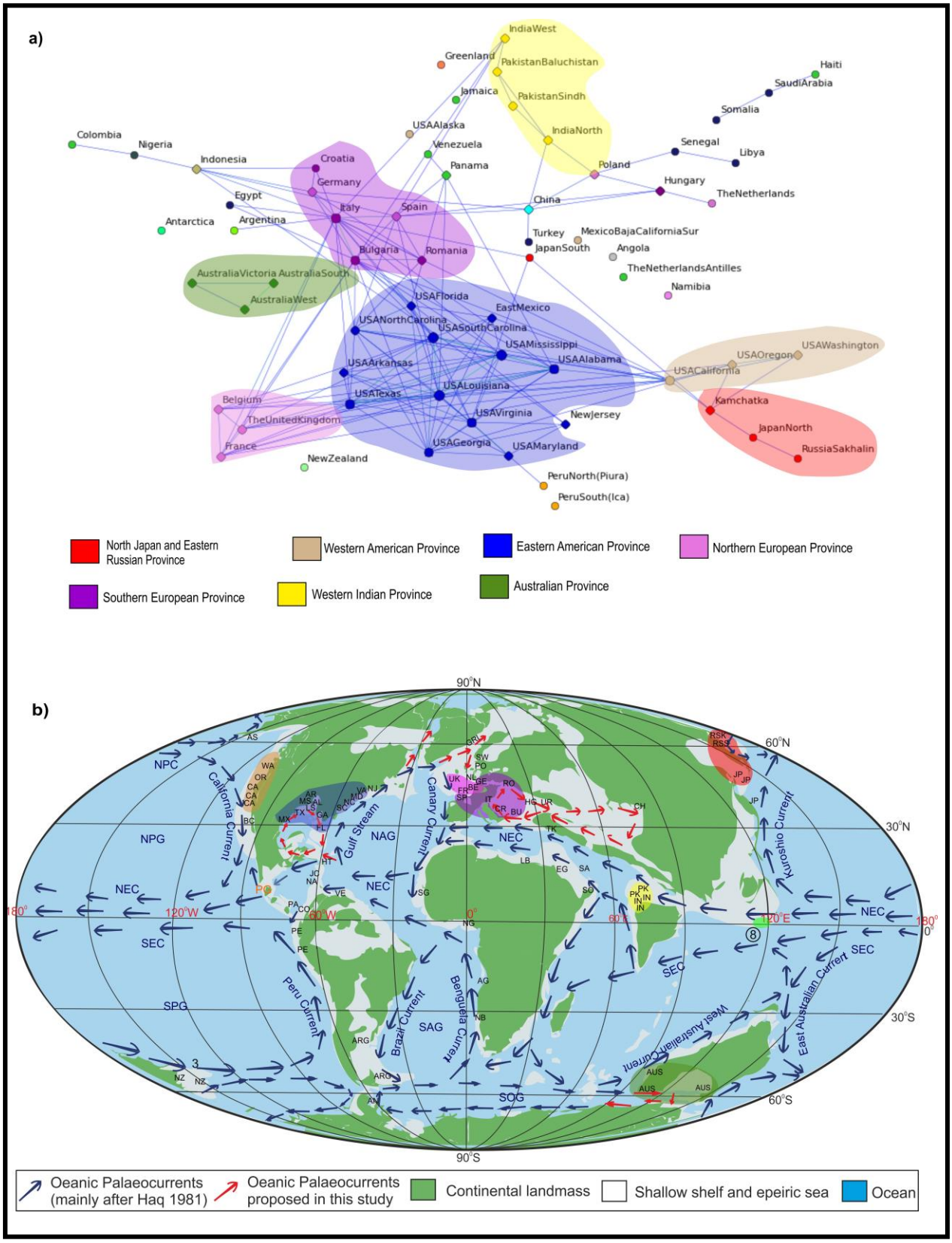

Figure 6. Palaeobiogeographic provinces defined by distinct colours a) in network analysis, performed in generic level of all the bivalves present in Eocene (executed by EdeNetworks) b) palaeocoastline map of Eocene (~50Ma) (Scotese et al. 2016).

Panama Gateway (PG) between the two American continents during the Paleogene is indicated by persistent similarity between the provinces on the Atlantic and the Pacific coasts of North America (Figures 5b, 6b, 7b).

The European, Middle Eastern and Western Indian basins display broad similarity through the Paleogene reflecting their Tethyan inheritance and continuation of connectivity (Figures 5, 6, 7). Most of the Middle Eastern basins lost considerable amount of faunal diversity and the connection between western India and Europe-America got weakened due to the shallowing of Tethyan gateway during Oligocene.

Migration, appearance and extinction of bivalves from each of the 10^0 latitudes in the Paleocene-Eocene (P-E) and Eocene-Oligocene (E-O) boundaries have been calculated (Figure 8.3). PETM did not affect bivalve generic diversity very adversely. The extinction at the P-E transition eliminated mainly high latitude faunas while low latitude faunas migrated to higher latitudes. Concomitant transgressions, on the other hand, encouraged diversification in tropical and subtropical latitudes. The global cooling at E-O transition caused an elevated degree of extinction as it affected a diverse tropical biota of the Eocene. The forms that survived the extinction exhibited a tendency to contract their ranges from high latitudes. The concomitant regression facilitated the extinction and discouraged diversification. The migration in the epoch boundaries were not solely dependent upon temperature gradient. Oceanic current pattern and tectonism also played an important role.

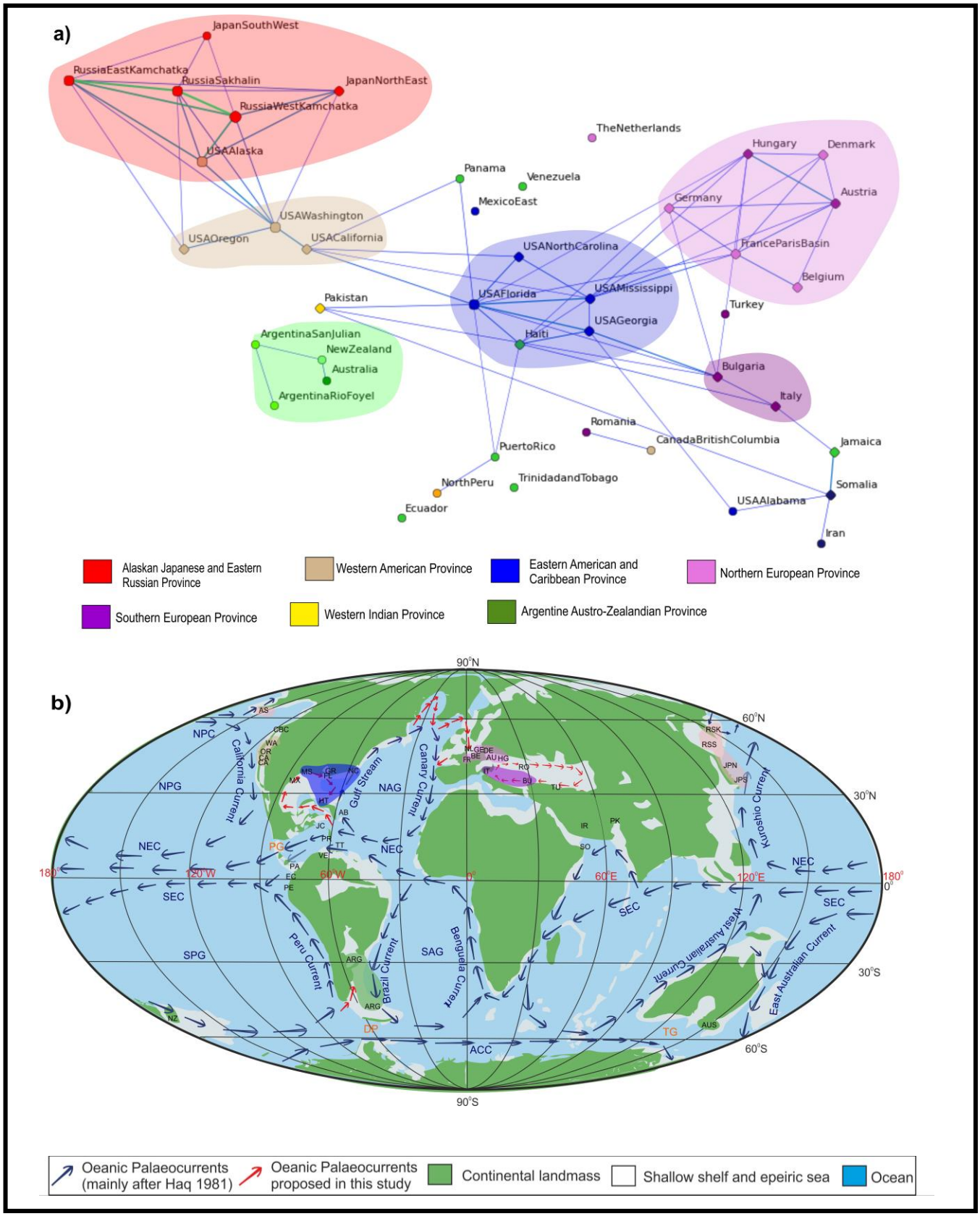

Figure 7. Palaeobiogeographic provinces defined by distinct colours a) in network analysis, performed in generic level of all the bivalves present in Oligocene (executed by EdeNetworks) b) palaeocoastline map of Oligocene (~30Ma) (Scotese et al. 2016).

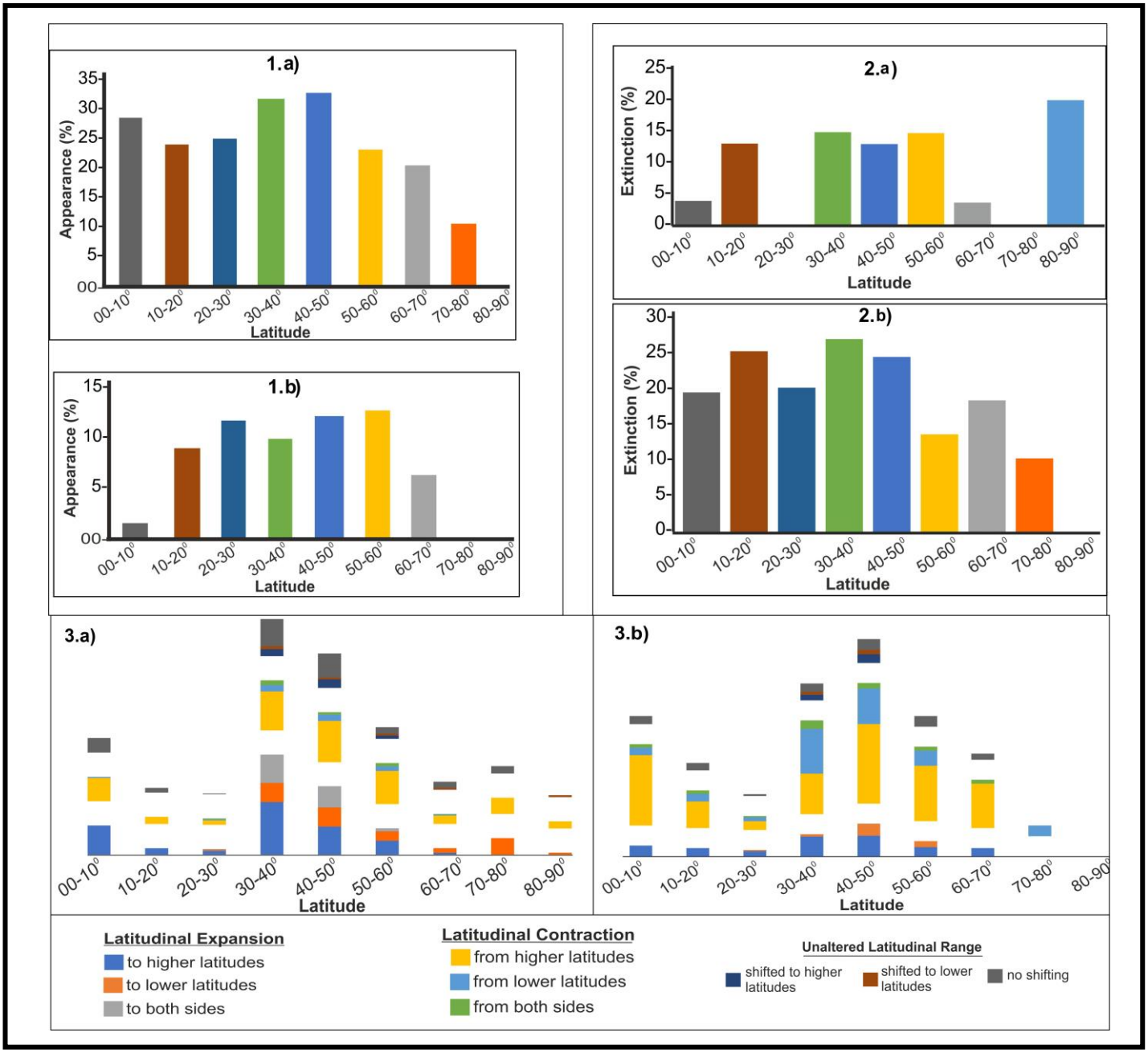

Figure 8. 1. Appearance of new genera in different latitudinal ranges in a) Paleocene-Eocene boundary and b) Eocene-Oligocene boundary; 2. Extinction of genera in different latitudinal ranges in a) Paleocene-Eocene boundary and b) Eocene-Oligocene boundary; 3. Stacked bar diagram of latitudinal distribution change in a) Paleocene-Eocene boundary b) Eocene-Oligocene boundary.

Paleocene		Eocene		Oligocene	
Province	**Localities**	**Province**	**Localities**	**Province**	**Localities**
Eastern American Province	USA - New Jersey, Maryland, Virginia (Atlantic coast basin Baltymore Canyon); Tennessee, Georgia	**Eastern American Province**	USA – North Carolina, New Jersey, Maryland, Virginia, (Atlantic coast basin Baltymore Canyon); South Carolina (Atlantic Coast Basin Blake Plateau); Georgia, Alabama, Texas, Mississippi, Arkansas, Louisiana, Florida (Gulf Coast Basin); East Mexico (Gulf Coast Basin)	**Eastern American and Caribbean Province**	USA –Georgia, Mississippi, Florida (Gulf Coast Basin); North Carolina (Atlantic coast basin Baltymore Canyon), Haiti (Beata Basin)
Gulf Coastal Province	Louisiana, Alabama, Texas and Midway group of East Mexico (Gulf Coast Basin)				
Caribbean and South Carolina Province	Trinidad and Tobago (Tobago Basin), USA- South Carolina (Atlantic coast basin Blake Plateau)				
		Western American Province	USA – Oregon, Washington, California	**Western American Province**	USA – Oregon, Washington, California
Polish Province	South Poland (Vistula Valley), North Poland (North Sea Basin)	**Northern European Province**	United Kingdom (London Basin, Hampstead cliff Hampshire Basin), France (Paris Basin), Belgium (Brussels Basin)	**Northern European Province**	Germany (Neuwieder Becken, South German Mollasse Basin), Belgium (North Sea Basin); France (Paris Basin), Austria (Upper Austrian Molasse Basin), Hungary (Upper Rhinegraben and Jura Mountains), Denmark (North Sea Denmark Basin)
Western European Province	East Belgium (Calaire de Eisden Formation, Eisden Region), West Belgium (Sophia Jacoba), Germany (North Sea Basin); France (Paris Basin)	**Southern European Province**	Italy (Colli Berici), Croatia (Promina); Germany (Gehlberg Fm, Silberberg Formation, Helmstedt-Oschersleber Depression) Bulgaria (Moesian Platform), Romania (Transylvanian Basin), Spain (Pyrenean foreland)	**Southern European Province**	Italy (Majella Platform, Piedmont Basin), Bulgaria (Moesian Platform)
Western Indian Province	Pakistan (Indus Valley Basin), India (Kutch Basin)	**Western Indian Province**	West India- Rajasthan, Kutch and Cambay basin; North India- Subathu; Pakistan- Indus Valley Basin		
Eastern Russian Province	Russia- Kamchatka, Sakhalin	**North Japan and Eastern Russian Province**	Japan North (Hokkaido), Russia- Sakhalin, Kamchatka	**Alaskan, Japanese and Eastern Russian Province**	North Japan (Hokkaido); South Japan (Koshiki Islands); Russia - Kamchatka, Sakhalin; Alaska (Yakutat Terrane, Gulf of Alaska and Alaska Peninsula)
		Australian Province	Australia- Victoria (Otway Basin), Southwest Australia (Perth Basin), Western Australia (Carnarvon Basin)	**Argentine Austro-Zealandian Province**	Argentina - San Julian (San Julian Basin), Rio Foyel (Neuquen Basin); Australia (Otway Basin); New Zealand (North and South Island),

Table 1. The changing architecture of the palaeobiogeographic provinces in the three epochs of Paleogene

2. Species from the Western part of Indian Subcontinent: The Ypresian bivalve species from Kutch and Cambay exhibit maximum affinity to the late Paleocene to early Eocene faunas from other basins of the western part of Indian subcontinent, especially Sindh, Pakistan. Some of them have also been found from the middle Eocene of western Tethys basins (Figure 9.1). The more eastern localities like Manipur of India, Mayanmar, Java and Borneo host these species only in the late Eocene. The larval dispersal through oceanic currents were mainly from east to west, which is reflected in the abundance of Ypresian species from Kutch and Cambay appearing increasingly in the European and east African localities in Lutetian or younger stratigraphic levels (Figure 9.1). The paleocurrent pattern established by Haq (1987) and our generic study also support this east to west dispersal of planktonic larva. The Priabonian bivalves from eastern localities like Manipur, Myanmar, Java and Borneo show some similarities with bivalves from earlier parts of Eocene from Cambay and Kutch. This was facilitated by the South Equatorial Current and Indian Counter Current after the closure of Tethys Sea ~ 40Ma (Figure 9.1,2).

Among the 334 Eocene bivalve species of Western Indian Province (WIP), 271 (81%) were restricted within the province itself. The species also show strong endemism to individual basin/ sub-basins. 76% of the species were endemic to only one out of eight basin/ sub-basins of WIP. However, the basins, except Hazara sub-basin, were connected by the same water body (Figure 9.2) (Malkani and Mahmood, 2016). Among the four basins within Indian political boundary, Jaisalmer and Subathu share maximum species with Sulaiman, Kirthar and Kohat-Patwar sub-basins of Pakistan. Cambay and Kutch were connected to this community, but depict lower level of specific similarity. Kutch being geographically closer to the Pakistan basins, had a relatively stronger bond than the Cambay basin (Figure 9.3).

Among the 78 bivalves of WIP, which are shared between more than one basin/ sub-basin, 43 are shared between two. Only one species is shared between seven basin/ sub-basins. This pattern of high endemism indicates low dispersibility and/or rapid allopatric speciation.

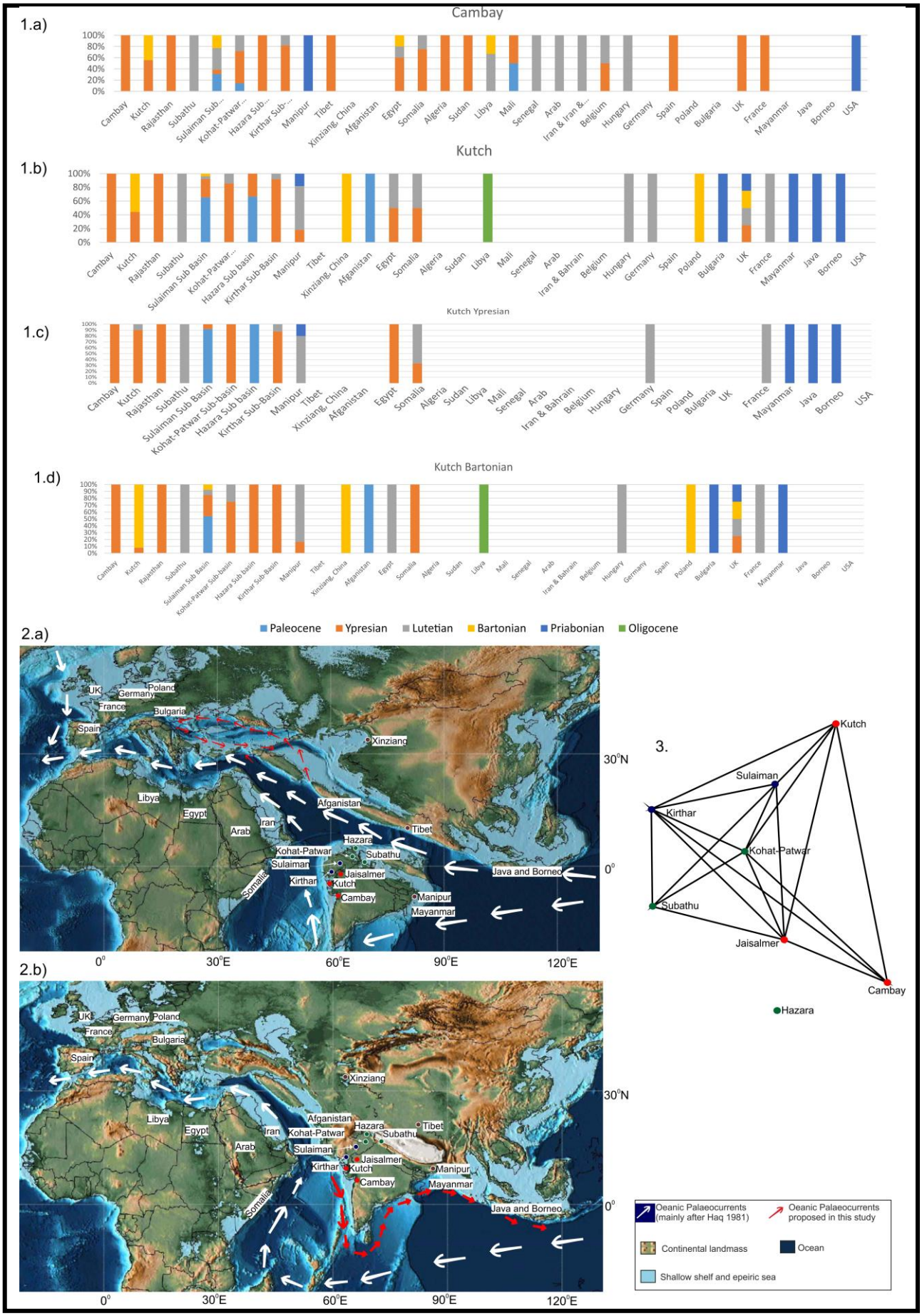

Figure 9. Species level palaeobiogeographic study. 1) Distribution of the Cambay and Kutch basin bivalve species globally with time; 2) Palaeocoastline map of and around Indian subcontinent (from Scotese et al. 2016) a) during Ypresian (~56-47Ma) and b) during Bartonian-Priabonian (~41-34Ma); 3) Network analysis in between the basins/sub-basins of western Indian province incorporating all the bivalve species present in that region during Eocene.

Abbreviations: DP- Drake Passage; TG- Tasman Gateway; CIE- Carbon Isotope Excursion; P-E – Paleocene-Eocene Boundary; LS- Lignite Seam; SB- Shell Bed; TOC- Total Organic Carbon; GMSL: Global Mean Sea Level; ACC- Antarctic Circumpolar Current; NPG- Northern Pacific Gyre; NAG- Northern Atlantic Gyre; PG- Panama Gateway; WIP- Western Indian Province. Institutional Abbreviation: PG/CB/P- Paleogene Cambay Bivalves of Presidency University Geology Department.

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